Further improvement in a criterion for human stability in floodwaters

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Abstract

There have been numerous urban flood disasters in recent years, causing a considerable loss of human life. An improved criterion in the form of incipient velocity has been proposed for human stability in floodwaters, and it is specifically for deep waters where toppling instability generally occurs, and it can account for the posture of leaning forward of a human body in floodwater and the process of pivoting around heels at instability. Moreover, the previous equation of buoyancy force was modified using the parameters of human body structure for a typical American or European in ergonomics. Two parameters in the formula of incipient velocity were calibrated using existing experimental data based on real human subjects, with the improved stability criterion curves being presented for children and adults in floodwaters. Finally, the proposed formula was validated in detail against existing laboratory measurements, and the simple method was given to evaluate the flood hazard degrees for children and adults, based on the calculated incipient velocities at toppling instability and the corresponding incoming flow velocities.

Keywords: urban flood; human stability; incipient velocity; mechanics-based analysis

1 Introduction

The intensification in natural hydrologic processes are contributing to cause extreme urban floods to be one of the most devastating hazards throughout the world, owing to the global climate change and the increasing density of population in flood-prone areas. According to the EM-DAT (2015), there were a total of 3557 flood events reported in the period 1986-2015 around the world, which met the EM-DAT criteria for severity; these floods caused about two hundred thousand deaths. For example, a flood occurring in Aragon of Spain wiped out the Biescas' campground on 7 August 1996, which killed more than 80 persons (Soula et al., 1998). An excessive regional rain in October 2003 caused catastrophic flooding in France, Swiss and Italian Alps, with a loss of 29 lives and an estimated damage in excess of $8 billion (Barredo, 2007). More than 600 mm of rain fell in less than 24 hours in 2002, which led to a series of flash floods in the Gard River, France, with 23 fatalities and 1.2 billion Euros of damages being reported (Ruin et al., 2008). More recently, a flash flood owing to an extraordinary rainfall occurred in Beijing in July 2012, and the mean rainfall reached 170 mm over a period of 20 hours, with a maximum rainfall of 460 mm in the district of Fangshan. The direct economic loss from this flood event was estimated to exceed $1.86 billion and more than 1.6 million people were affected by the floodwaters, with a loss of about 80 human lives being reported (Wang et al., 2013; Xia et al., 2016). People safety can be compromised when they are exposed to floodwaters that exceed their ability to remain standing. Therefore, it is significant to propose a quantitative method to assess the stability degree of a human body in floodwater, which can provide a scientific basis for the flood risk assessment.

Various experiments have been conducted over the past decades in an attempt to quantify the criterion for human stability in floodwaters. Foster and Cox (1973) firstly studied this issue by testing the stability of six children with different height and mass combinations in a laboratory flume and found that physical, emotional and dynamic factors significantly influence the degree of human stability in floodwaters. The measurements of Foster and Cox (1973) also indicated that the instability was mainly caused by sliding since the tests were performed under high flow velocities and low water depths. Abt et al. (1989) conducted further tests and found that the mechanism of toppling would also be a key cause of human instability in floodwaters with higher depths. Takahashi et al. (1992) conducted detailed measurements on the friction coefficient for a range of leather and rubber soled shoes on various ground surfaces, when testing the safety of dock workers under the condition of wave overtopping on harbor structures. By conducting human stability experiments in a 130 m long laboratory basin, Karvonen et al. (2000) concluded that human stability might be influenced by other factors such as lighting and turbidity. Yee (2003) carried out stability testing of 4 young children in a laboratory flume, and it was deemed that the lower stability of a younger human subject was due to a lower level of muscular development and coordination. Russo et al. (2013) constructed a laboratory model representing a near-full-scale urban street for investigating the stability of pedestrians during storm events, with a new criterion for human stability being developed based on these experimental data, and it was concluded that several existing studies in flumes for hazard assessment on floodplains seem to overestimate human stability degrees in urban floods (e.g. Foster and Cox , 1973; Abt et al., 1989; Karvonen et al., 2000; Takahashi et al., 1992; Yee, 2003; Jonkman and Penning-Rowsell, 2008). Martínez-Gomariz et al. (2016) conducted the tests similar to the experiments of Russo et al. (2013), and general hazard levels for pedestrians crossing a street were established under various combinations of water depth and velocity, which accounted for various classifications of footwear, test subject age and weight, and visibility conditions.

Due to the limitations in laboratory-based experimental studies, some empirical and theoretical methods were introduced to investigate the human stability criteria. Jonkman and Penning-Rowsell (2008) tested the stability of an adult stuntman in a real channel and proposed a simplified stability criterion, with the modes of both sliding and toppling instability being included, however, the effect of buoyancy force was neglected. Milanesi (2015) established a conceptual model that accounted for the destabilizing effect of local slope and fluid density. Recently, Xia et al. (2014) derived two mechanics-based formulae for the incipient velocity of a human body on a horizontal ground at instability modes of sliding and toppling, with the buoyancy force being included in the derivation, and the calculated results were compared with existing experimental data based on American or European subjects.

However, the majority of the previous theoretical studies did not account for the maneuverability of human bodies in floodwaters. In the real condition, pedestrians in floodwaters can adjust their positions or postures to brace against the water, thereby resulting in them resisting larger flows. This conclusion is supported by the study of Jonkman and Penning Rowsell (2008), and it was observed that: a subject first stood at right angles to the flow in the standing test; as the flow and depth increased, the subject swiveled so as to stand diagonally to the flow, with one leg in front of the other and with the front leg bent, and then leaned forwards so as to lower his center of gravity. Therefore, the postural adjustment of a human body in floodwater cannot be neglected in the theoretical analysis because it can influence the stability degree of a human body. It should be noted that the current work is an improvement on the previous study of Xia et al. (2014), which further accounts for the postural adjustment of a human body in floodwater.

Another aspect should be noted that in the work of Xia et al. (2014), the buoyancy force was calculated based on the statistics of the body segment parameters for a Chinese in ergonomics due to the irregular shape of a human body. However, there exists a difference of body structure attributes between the typical American or European and the Chinese, thus an error is caused when the parameters calibrated by the average body attributes for a Chinese are used to estimate the buoyancy force acting on an American or European in floodwater. Therefore, it is necessary to revise the equation of buoyancy force based on the parameters of human body structure for a general American or European.

In the present study, the previous equation of buoyancy force is corrected further, with the parameters of human body structure being considered for a typical American or European. The postural adjustment of a human body in floodwater was conceptualized as a rigid body at a tilting angle to the flow. Different forces acting on a human body leaning forward the incoming flow are presented, with the corresponding formula being derived for incipient velocity at toppling instability. Two parameters in the formula of incipient velocity were calibrated based on previous experimental data, with the improved criterion being presented for the stability of children and adults in floodwaters. Finally, the value of the tilting angle of a human body in floodwater was discussed, and the proposed criterion for adults was validated in detail against existing laboratory measurements.

2 Force analysis and formula derivation

Previous studies have identified that there are two main mechanisms of human instability in floodwaters, including sliding (friction) instability and toppling (moment) instability. Sliding instability usually occurs in high-velocity shallow waters, while toppling instability generally occurs in deeper waters (Keller and Mitsch, 1993; Cox et al., 2010; Xia et al., 2014). Jonkman and Penning-Rowell (2008) presented another hydrostatic mechanism for completeness: floating. They pointed out that floating usually occurs when water depth exceeds a person's height, as the density of the human body is similar to the density of water, and then, the person is no longer subject to the influence of moment or friction instability. Limited measurements under the mode of sliding instability were obtained from the literature. Therefore, the current study only focuses on the mode of toppling instability for a human body in floodwater. In this section, the corresponding expressions are presented for the forces acting on a human body in floodwater. Based on the mechanisms of toppling instability and the principles of river dynamics, an incipient velocity formula is derived, with the postural adjustment of a human body in floodwater being considered.

2.1 Forces acting on a human body in floodwater

The force analysis for the stability of a human body in floodwater at toppling instability is similar to the method for the derivation of the incipient motion of a coarse sediment particle at rolling in river dynamics (Zhang and Xie, 1993). The forces acting on a human body include the drag force ($\boldsymbol{F_D}$) of the flowing water in the streamwise direction, the gravitational force ($\boldsymbol{F_G}$) and buoyancy force ($\boldsymbol{F_b}$) in the vertical direction. In addition, the body also experiences the normal reaction force from the ground ($\boldsymbol{F_N}$) (see Fig. 1). Toppling instability generally occurs when the moment exerted by the drag force exceeds the resisting moment of the effective body weight (Abt et al., 1989; Lind et al., 2004; Cox et al., 2010).

As pointed by Jonkman and Penning Rowsell (2008), the postural adaptation of a human body to the flow is a dynamic and complex process, therefore it's difficult to include the total reaction of the body in the theoretical analysis. To simplify the process and improve the usability of the results, the current analysis accounts for the most relevant influencing factor, i.e. the inclination of a human body at an angle facing the incoming flow, and adopts a static mode to analyze the human stability characteristic. As shown in Fig. 1, the postural adjustment of a human body in floodwater is simplified to a rigid body at a tilting angle (θ) to the incoming flow, with the values of θ being not more than 90°. When toppling instability occurs, the body will start to rotate around the heels. Buoyancy force is the product of water density ρ_f, acceleration of gravity g and the volume of the displaced water by the partially submerged human body V_b, which can be written as:

$$F_b = \rho_f g V_b \tag{1}$$

where the water density (ρ_f) is usually set to 1000 kg/m^3. It is clear that V_b is related to the water depth (h_f), the height (h_p) and the total volume (V_p) of a human body. In terms of ergonomics, there exist various empirical relationships between the sizes of various segments of a typical human body, and h_p or V_p (Drillis et al., 1964; Guo and Wang, 1995; Sandroy and Collison, 1996). Based on these characteristic parameters of the body structure, this relationship is usually represented by a quadratic function with sufficient accuracy, and with the corresponding function being written as:

$$V_b / V_p = a_1 (\frac{h_f}{h_p})^2 + b_1 (\frac{h_f}{h_p}) \tag{2}$$

where a_1 and b_1 are non-dimensional coefficients, which can be determined by the known volume of each body segment in ergonomics (Drillis et al., 1964). Based on the average adult body attributes for a European, the values of a_1 = 0.735 and b_1 = 0.265 are calibrated respectively (Fig. 2). Because of the scarcity of data for the segment parameters of a child body, it is assumed that the values of a_1 and b_1 for a child body are the same to those for an adult body.

There also exists an approximate linear relationship between the volume V_p [m^3] and the mass m_p [kg] of a human body in ergonomics, which can be expressed by:

$$V_p = a_2 m_p + b_2 \tag{3}$$

where a_2 and b_2 are empirical coefficients, and $a_2 = 1.015\times10^{-3}$ m^3/kg and $b_2 = -4.927\times10^{-3}$ m^3 are determined respectively based on the average attributes of a human body (Guo and Wang, 1995). Substituting Eqs. (2) and (3) into Eq. (1), the expression for the buoyancy force can then be re-written as:

$$F_b = g\rho_f [a_1 (\frac{h_f}{h_p})^2 + b_1 (\frac{h_f}{h_p})](a_2 m_p + b_2) \tag{4}$$

The calculation of the buoyancy force using Eq. (4) fully accounts for the effect of an irregular body shape. Considering the situation of a human body with a mass of 60 kg standing in floodwater, the buoyancy force calculated using Eq. (4) is equivalent to 26% of the gravitational force under the condition of a waist-deep water. Therefore, it is necessary to include the effect of the buoyancy force when deriving the stability criterion for a human body in floodwater.

In the streamwise direction, the drag force ($\boldsymbol{F_D}$) acting on a human body in floodwater can be written as:

$$F_D = 0.5 A_d C_d \rho_f u_b^2 \tag{5}$$

where u_b is a representative near-bed velocity; C_d is the drag coefficient; and A_d is the wetted area, with $A_d = a_d\ (b_p h_f)$, where a_d is an empirical coefficient, with b_p being the average body width exposed normal to the incoming flow. Based on the statistics of the body segment parameters, a quantitative relationship between the mean body width and body height is expressed by $b_p = a_p h_p$, where a_p is an empirical coefficient. Therefore, the expression $A_d = a_d a_p\ (h_p h_f)$ can be obtained.

The gravitational force of a human body is the product of acceleration of gravity and body mass. For a human body leaning forward in floodwater, it is considered that under a partially submerged condition, the action position of the buoyancy force is not in line with the body gravity force along the vertical direction, as shown in Fig. 1. The buoyancy force and the body weight force act along the same line of action only if a human body is fully submerged in floodwater. The components of F_G in the x and y directions (F_{Gx} and F_{Gy}) are thus expressed respectively by:

$$F_{Gx} = (g m_p)\cos\theta \quad \text{and} \quad F_{Gy} = (g m_p)\sin\theta \tag{6}$$

Similarly, the components of F_b in the x and y directions (F_{bx} and F_{by}) are written respectively as:

$$F_{bx} = F_b\cos\theta \quad \text{and} \quad F_{by} = F_b\sin\theta \tag{7}$$

F_N is the normal reaction force from the ground surface, which is generally equivalent to the composite force of the gravitational force and the buoyancy force, wherein $F_N = F_G - F_\text{b}$.

2.2 Formula derivation at toppling instability

The critical condition for toppling instability is that the human body would pivot around the heel (Fig. 1), when the moment associated with the drag force and the buoyancy force is equal to the resisting moment from the body weight. Therefore, the corresponding moment balance equation at toppling instability can be written as:

$$F_{Gx} L_{gx} + F_{Gy} L_{gy} = F_D L_d + F_{bx} L_{bx} + F_{by} L_{by} \tag{8}$$

where L_{gx} and L_{gy} are the moment arm of the body weight along the x and y directions, respectively; L_d is the moment arm of the drag force, with $L_d = a_h h_f$, in which a_h is the correction coefficient for the height between the centre of the drag force and the ground surface; L_{gx} is the moment arm of the body weight along the x direction, with $L_{gx} = a_{gx}h_p$, and a_{gx} is the correction coefficient for the distance between the gravity centre of the body and the bottom, which is approximately equal to 0.55 based on the studies of Hellebrandt et al. (1938); L_{gy} is the moment arm of the body weight along the y direction, with $L_{gy} = a_{gy}h_p$, where a_{gy} is the correction coefficient for the distance between the position of the centre of gravity of the body and the heel. According to the statistics for the structure of a typical human body, the value of a_{gy} is typically about 0.05 (Guo and Wang, 1995) ; L_{bx} is the moment arm of the buoyancy force along the x direction, with $L_{bx} = a_{bx}h_f$, and a_{bx} is considered to be equal to a_{gx}, which can guarantee that the buoyancy force and the body weight force act along the same line of action when a human body is fully submerged in floodwater; L_{by} is the moment arm of the buoyancy force along the y direction, with $L_{by} = L_{gy}$ being assumed. Substitution of the expressions for L_d, L_{gx}, L_{gy}, L_{bx} and L_{by} (as shown in Fig. 1) into Eq. (8), the expression of u_b can be re-arranged as:

$$u_b = \sqrt{\frac{2ga_{gy}}{a_h a_d a_p C_d}}\sqrt{\frac{m_p}{\rho_f h_f^2}(\gamma\cos\theta+\sin\theta)-[a_1(\frac{h_f}{h_p})^2+b_1(\frac{h_f}{h_p})](a_2 m_p+b_2)(\frac{\gamma\cos\theta}{h_f h_p}+\frac{\sin\theta}{h_f^2})} \tag{9}$$

where $\gamma = a_{gx} / a_{gy}$. According to the values of a_{gx} and a_{gy}, the value of γ is set to a constant value of 10.0 in this study.

The representative near-bed velocity u_b cannot be determined easily in practice, and therefore the depth-averaged velocity (U) is generally used for simplicity. The incoming flow velocity distribution upstream of the body can be approximately characterized by a power-law velocity profile, but this refers to the flow velocity distribution before it reaches the zone with a high pressure gradient occurring around the submerged human body (Xia et al., 2014). The power-law velocity profile can be expressed as $u = (1+\beta)\ U\ (y/h_f)^{\beta}$, in which β is an empirical coefficient and can be determined by the inflow velocity profile; y is the height from the ground, and u is the velocity at y (Zhang and Xie, 1993; Wu, 2007). In this analysis, the representative height for u_b is set to $a_b h_p$, which gives $u_b = (1+\beta)\ U_c\ (a_b h_p / h_f)^{\beta}$, where a_b is a small coefficient related to the body height. Substituting the expressions for u_b into Eq. (9), the incipient velocity at toppling instability for a human body leaning forward in floodwater can be written as:

$$U_c = \alpha(\frac{h_f}{h_p})^{\beta}\sqrt{\frac{m_p}{\rho_f h_f^2}(\gamma\cos\theta+\sin\theta)-[a_1(\frac{h_f}{h_p})^2+b_1(\frac{h_f}{h_p})](a_2 m_p+b_2)(\frac{\gamma\cos\theta}{h_f h_p}+\frac{\sin\theta}{h_f^2})} \tag{10}$$

where $\alpha = \sqrt{2ga_{gy} / (a_d a_p C_d a_h)} / [(1+\beta)a_b^{\beta}]$. It should be noted that Eq. (10) is valid for the water depths h_f less than the human body's height h_p. As the tilting angle is assumed to be equal to 90°, Eq. (10) can be re-written as:

$$U_c = \alpha (\frac{h_f}{h_p})^{\beta} \sqrt{\frac{m_p}{\rho_f h_f^2} - (\frac{a_1}{h_p^2} + \frac{b_1}{h_f h_p})(a_2 m_p + b_2)} \tag{11}$$

Eq. (11) describes the toppling stability criterion of a human body standing at a right angle to the flow, which is coincident with the formula proposed earlier by Xia et al. (2014).

3 Parameter calibration and discussion

3.1 Parameter calibration

The structure of the formula presented in Eq. (10) is relatively complex due to the introduction of the buoyancy force and the inclination posture of a human body. For a particular human body, the value of mass (m_p) or height (h_p) is known, and the coefficients relevant to the body structure (i.e. a_1, b_1, a_2, b_2) in Eq. (10) have been evaluated according to the data from the ergonomics based on a typical European or American. The tilting angle of the body (θ) to the flow is actually a variable, which mainly depends on the forces acting on the object and the body’s manoeuvrability to adapt to the flow. However, the value of the tilting angle is set to 75° for a convenient use in the current investigation, and a thorough discussion of the selection of the tilting angle is presented in the next section. The process of formula derivation shows that the parameter α is theoretically not related to the tilting angle of a human body (θ) in floodwater, as the drag coefficient (C_d) is a constant for high values of the object Reynolds number and the parameter β is determined by the inflow velocity profile, and other coefficients (i.e. a_{gy}, a_d, a_p, a_h, a_b) are only related to the attributes of a human body (Xia et al., 2016). Therefore, the values of α and β can be calibrated using the software package SPSS based on the measurements in the literature (Abt et al., 1989; Karvonen et al., 2000).

Abt et al. (1989) undertook laboratory testing of 20 adults in flows under two bottom slopes of 0.5 and 1.5%, with four different bottom surfaces, and the datasets for a concrete bottom slope of 1.5% were used for parameter calibration. The calibrated values of α = 3.672 $m^{0.5}$/s and β = 0.271 were obtained, together with a relatively high value of R^2 = 0.712 (Table 1). Jonkman and Penning-Rowsell

(2008) developed a formula for estimating the incipient velocity at toppling instability, and this formula did not account for the effects of the buoyancy force acting on the human body and the non-uniform velocity profile along the vertical direction. Coefficients in the formula of Jonkman and Penning-Rowsell (2008) were also calibrated using the same experimental data of Abt et al. (1989), with R^2 = 0.62, which is less than the correlation degree (R^2 = 0.712) obtained in this study. Based on all the tests of Abt et al. (1989), Xia et al. (2014) calibrated the parameters in the incipient velocity formula at toppling instability, with a posture of human body standing upright in floodwater being considered, with R^2 = 0.561 being obtained. The lower degree of correlation calibrated by Xia et al. (2014) could be partly attributed to the ignorance of the body structure difference between a general Chinese and a typical European or American, as well as the inclining posture of human body. Moreover, the role of the tilting angle in Eq.(10) is much more important than the difference between the body's structure attributes of a Western person and an Asian person. Incipient velocities calculated using Eq. (11) can vary in less than 3% for the parameters of human body structure (namely, a_1 and b_1) obtained from the Western and the Asian, under the case of a person standing in floodwater with the body' height and weight of 1.77 m and 75.1 kg, respectively. However, Eq. (10) also reveals that the magnitude of incipient velocity is significantly sensitive to the assumed value of θ. For instance, under the water depth of 0.7 m, there is a variation in the incipient velocity of about 30.5%, with the value of θ decreasing from 75° to 60°. An increase of the value of θ by only 5° (i.e., θ = 80°) can cause the incipient velocity to reduce by 12.4%. It should be pointed out that although the current study considered the difference in body structure between the Western and the Asian, the role of the race difference is negligible, as compared with the tilting angle of a human body in floodwater.

Karvonen et al. (2000) tested the stability of 7 adults in floodwaters with different postures of standing, walking and turning, and 34 runs among the experimental datasets with the postures of standing and walking were used to evaluate the parameters in Eq. (10), the values of α = 2.471 $m^{0.5}/s$ and β = 0.202 were then calibrated, with a high value of R^2 = 0.959 being obtained (Table 1), which is higher than the correlation degrees of R^2 = 0.75 and R^2 = 0.922, calibrated respectively by Jonkman and Penning-Rowsell (2008) and Xia et al. (2014). Figure 3 shows a comparison between the measured incipient velocities and the values calculated using Eq. (10).

3.2 Discussion of the tilting angle

When the water depth is zero, the forces acting on a human body include the gravitational force and the ground reaction force (see Fig. 1). Therefore, to keep the human body stable, the centre of gravity on body must be located in the vertical range of the contact surface. This leads to:

$$L_{gx} \cdot \cos\theta \le L_{foot} - L_{gy} \tag{12}$$

where L_{foot} is the foot length, which is approximately equal to $0.15h_{\text{p}}$; and the value of θ is not much lower than 90°. Substituting the expressions of L_{foot}, L_{gx} and L_{gy} into Eq. (12), the range of the value of θ can be obtained:

$$79.5° \le \theta \le 90° \tag{13}$$

Eq. (13) shows that the minimal tilting angle for a typical human body is 79.5° with no water on the ground. It should be noted that the above analysis is based on the theory of mechanics, with the human body being considered as a rigid model and no force from the water acting on the body. However, in the condition of the person resisting against the water, the critical tilting angle of a human body (θ) in Eq. (10) would be less than 79.5°.

Experimental data of a total 86 tests at toppling instability (Abt et al., 1989; Takahashi et al., 1992; Karvonen et al, 2000; Yee, 2003) were used to calibrate and verify the parameters α and β under different values of θ. 74 runs among these tests were used to calibrate the parameters α and β under different values of θ ranging from 55° to 90°, with the calibrated results being presented in Table 2. The previous derivation process of the proposed formula shows that the parameter α and β are independent of the value of θ . However, Table 2 shows that the values of α and β vary with the change of θ. These variations are regarded to be caused by different test conditions and subjects in the experiments. To obtain the unified values for α and β, a simple method of arithmetic averaging was used, with the mean values for these parameters (namely α=3.064 and β=0.303) being evaluated. These unified parameters are suggested to be used in the assessment of flood hazard risk for adults and children.

Another 12 runs were used to verify the accuracy of the calibrated formula at different values of θ, covering a wide range of the values of Fr. Froude number (Fr) is a criterion of the flow regime, with the flow being defined as supercritical for $Fr > 1$ and being characterized as subcritical for $Fr < 1$. For each value of θ, the incipient velocities were calculated based on the experimental data of these 12 runs and the unified values for α and β. Then the variations (V) between the calculated incipient velocity (U_{cc}) and the measured incipient velocity (U_{cm}) were obtained at each value of θ, with $V=\frac{1}{12}\sum_{i=1}^{12}(U_{cci}-U_{cmi})^2$. The relationship between the tilting angle of a human body (θ) and the variation (V) was presented in Fig. 4. Figure 4 illustrates that the variation reaches the lowest point when θ is approximately equal to 75°. The comparison between the calculated and measured values of the incipient velocities was presented in Fig. 5, and it also shows that the calculations agree better with the measurements when the value of θ is equal to 75°. Therefore, it is appropriate to use the unified α and β at θ=75° to calculate the incipient velocity for a human in floodwater. It should be emphasized that the value θ=75° doesn't mean a real person can keep the body rigid at a tilting angle of 75° in floodwater. The tilting angle is just a conceptual parameter representing the comprehensive posture of a human body in floodwater.

4 Application to laboratory measurements

The average body structure parameters for a typical adult or child were adopted in Eq. (10), with a mass of m_p = 75.1 kg or 25.5 kg, and a height of h_p =1.77 m or 1.26 m, respectively. The toppling stability thresholds for adults and children were illustrated respectively by the thin broken curve and the thick solid curve in Fig. 6. Figure 6 presents the observed datapoints of water depth and flow velocity for people at toppling instability, covering the laboratory measurements of Abt et al., 1989; Karvonen et al., 2000; Takahashi et al., 1992; Yee, 2003; Russo et al., 2013; Martínez-Gomariz et al., 2016.

Figure 6 shows that the calculated results generally agree well with the observed data obtained from the tests conducted in laboratory flumes (Abt et al., 1989; Takahashi et al., 1992; Karvonen et al., 2000; Yee, 2003, Jonkman and Penning-Rowsell, 2008), whereas the proposed stability guideline for adult is higher than the datasets of Russo et al. (2013) and Martínez-Gomariz et al. (2016), and this can be partly attributed to the fact that their experiments were conducted under the condition of low depth and high velocity. In addition, the specific characteristics of the experimental campaign (safety equipment, costume, footwear, ground surfaces, etc.) may also influence the results (Russo et al., 2013).

With the calibrated parameters α and β in Eq. (10), the proposed formula can be used to evaluate the flood hazard risk to people in urban floods with high water depths, and the predictions can be used in flood risk management. Specifically, for a given value of the incoming depth h_f, the corresponding incipient velocity for adults or children can be calculated using Eq. (10). If the incoming velocity exceeds the corresponding incipient velocity, then the adults or children will be swept away, otherwise they will be safe. These curves in Fig. 6 relating water depths and corresponding critical velocities divide the safe and unsafe regions for children or adults respectively. For example, the zone below the broken curve means safe for adults, while it would be unsafe above the curve. The formula can further be used to quantify the flood hazard degree (*HD*) for children and adults based on the following expression (Xia et al. 2011):

$$HD = \mathrm{Min}\ (1.0,\ U_{\mathrm{f}}\ /\ U_{\mathrm{c}}) \tag{14}$$

where U_{f} is the velocity of the incoming flow, which can be predicted using a two-dimensional hydrodynamic model for urban flood inundation. Obviously, the value of *HD* ranges from 0 to 1.0, and a higher *HD* value means more dangerous for people. This simple assessment method is useful for managers to issue the flood warning information in urban areas.

5 Conclusions

Urban flood disasters appear to have occurred frequently in recent years due to intense rainfall, leading to severe casualties. When exposed to floodwater, the person would adjust standing posture to increase the resistance to the incoming flow, commonly with a posture of leaning forward the incoming flow. However, previous studies relevant to the stability criteria for people in floodwaters have taken little or no consideration into the effect of postural adaptation of the human body. The criterion in the form of incipient velocity for human stability in floodwaters has been improved in this study, with the leaning posture being considered, which is regarded as a conceptual representation of the postural adjustment. The parameters in the proposed formula were calibrated based on the previous experimental data. The following conclusions are drawn from this study:

(i) The forces acting on a human body in floodwater with a posture of leaning forward were presented, with a corresponding formula for the incipient velocity being derived at toppling instability, which accounts for the effects of body buoyancy and standing posture. It is necessary to be noted that the test subjects in previous flume experiments were American or European, and there exists a slight difference of body structure between a general Chinese and a typical European or American. Therefore, the buoyancy force was re-evaluated based on the parameters of human body structure for a typical American or European.

(ii) The role of the tilting angle of a human body in floodwater was discussed and the parameters were re-calibrated based on existing flume experimental datasets for American or European human subjects. Stability thresholds at toppling for children and adults were presented in this study, based on the re-calibrated parameters using existing flume experimental datasets for American or European human subjects.

(iii) The flood hazard degrees for children and adults were further evaluated based on the calculated incipient velocities at people instability and the corresponding incoming flow velocities. This simple assessment method is useful for issuing the flood warning information in urban areas.

Acknowledgements

The study was partly supported by the National Natural Science Foundation of China (Grant Nos. 51725902 and 51579186), and the Key Cultivating Project from Wuhan University (Grant No. 2042017kf0238). It was also partly supported by two international projects of Global Challenges Research Fund at Cardiff University and UK-China Urban Flooding Research Impact Programme

References

Abt S.R., Wittler R.J., Taylor A., Love D.J. Human stability in a high flood hazard zone. Journal of the American Water Resources Association, 1989, 25(4), 881-890.

Barredo J.I. Major flood disasters in Europe: 1950–2005. Natural Hazards, 2007, 42(1), 125-148.

Cox R.J., Shand T.D., Blacka M.J. Appropriate safety criteria for people. Sydney: Engineers Australia, 2010.

Drillis R., Contini R., Bluestein M. Body segment parameters. Artificial Limbs, 1964, 8(1), 44-66.

EM-DAT: http://www.emdat.be/, 2015.

Foster D.N., Cox R.J. Stability of children on roads used as floodways. Sydney: Water Research Laboratory, 1973.

Guo Q.S., Wang Y.H. Ergonomics. Tianjing University Press, Tianjing, 1995.

Hellebrandt F.A., Tepper R.H., Braun G.L. Location of the Cardinal Anatomical Orientation Planes Passing Through the Center of Weight in Young Adult Women. American Journal of Physiology, 1938, 121, 465-470.

Jonkman S.N., Penning- Rowsell E. Human instability in flood flows. Journal of the American Water Resources Association, 2008, 44(5), 1208-1218.

Karvonen R.A., Hepojoki H.K., Huhta H.K., Louhio A. The use of physical models in dam-break analysis. Helsinki: Helsinki University of Technology, 2000.

Keller R.J., Mitsch B. (1993) Safety Aspects of the Design of Roadways as Floodways, Research Report No. 69.

Lind N., Hartford D., Assaf H. Hydrodynamic models of human stability in a flood. Journal of the American Water Resources Association, 2004, 40(1), 89–96.

Milanesi L., Pilotti M., Ranzi R. A conceptual model of people's vulnerability to floods. Water Resources Research, 2015, 51, 182-197.

Martínez-Gomariz E., Gómez M., Russo B. Experimental study of the stability of pedestrians exposed to urban pluvial flooding. Natural Hazards, 2016, 82(2), 1259-1278.

Ruin I., Creutin J.D., Anquetin S. and Lutoff C.L. Human exposure to flash floods–Relation between flood parameters and human vulnerability during a storm of September 2002 in Southern France. Journal of Hydrology, 2008, 361(1-2), 199-213.

Russo B., Gómez M., Macchione F. Pedestrian hazard criteria for flooded urban areas. Natural hazards, 2013, 69(1), 251-265.

Sandroy J., Collison H.A. Determination of human body volume from height and weight. Journal of Applied Physiology. 1996, 21(1), 167–172.

Soula S., Sauvageot H., Molinie G., Mesnard F., Chauzy S. The CG lightning activity of a storm causing a flash- flood. Geophysical research letters, 1998, 25(8), 1181-1184.

Takahashi S., Endoh K., Muro Z.I. Experimental study on people’s safety against overtopping waves on breakwaters. Report on the Port and Harbour Institute, 1992, 34(4), 4-31.

Xia J.Q., Falconer R.A., Wang Y.J., Xiao X.W. New criterion for the stability of a human body in floodwaters. Journal of Hydraulic Research, 2014, 52(1), 93-104.

Xia J.Q., Chen Q., Falconer R.A., Deng S.S., Guo P. Stability criterion for people in floods for various slopes. Proceedings of the Institution of Civil Engineers-Water Management, 2016, 169(4), 180-189.

Xia J.Q., Falconer R. A., Lin B., et al. Numerical assessment of flood hazard risk to people and vehicles in flash floods. Environmental Modelling & Software, 2011, 26(8), 987-998.

Yee M. Human stability in floodways. Sydney: University of New South Wales, 2003.

Zhang R.J., Xie J.H. Sedimentation research in China. China Water and Power Press, Beijing, 1993.

Wang K.,Wang L., Wei Y.M. and Ye M.S. Beijing storm of July 21, 2012: observations and reflections. Natural Hazards, 2013, 67(2), 969–974.

Wu W.M. Computational river dynamics. Taylor & Francis Group, London, 2007.

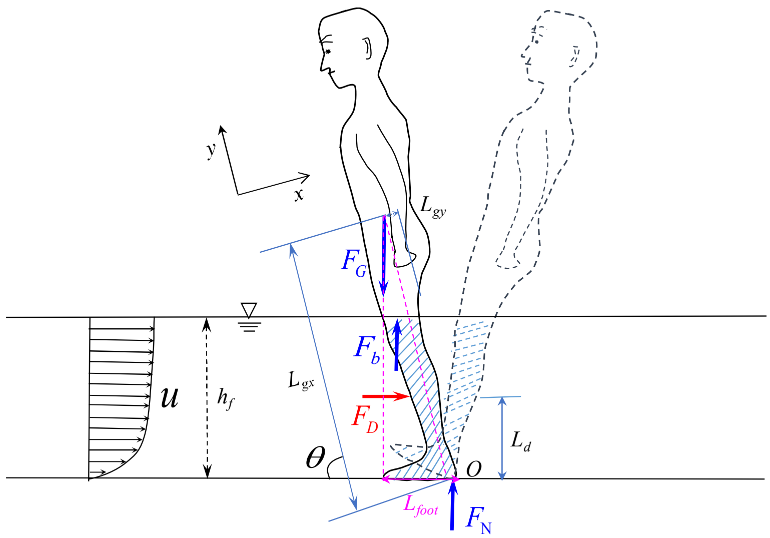

Figure 1. Sketch of governing forces acting on a flooded human body at toppling instability.

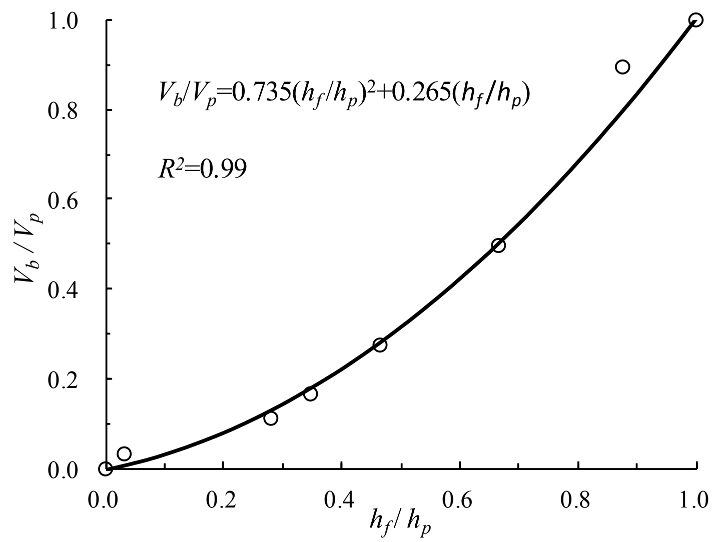

Figure 2. Relationship between the relative volume and relative depth for a typical European or American.

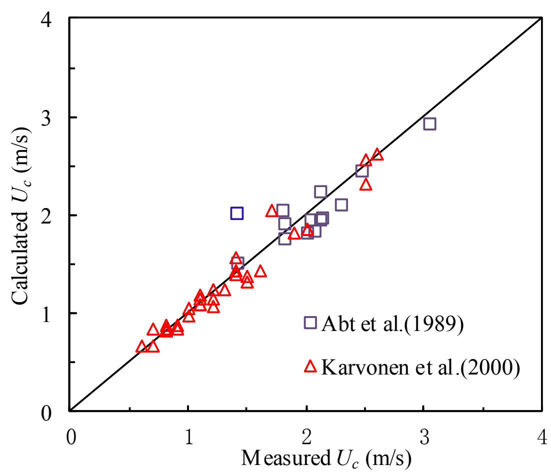

Figure 3. Comparison between the previous experimental data and the calculations using Eq. (10).

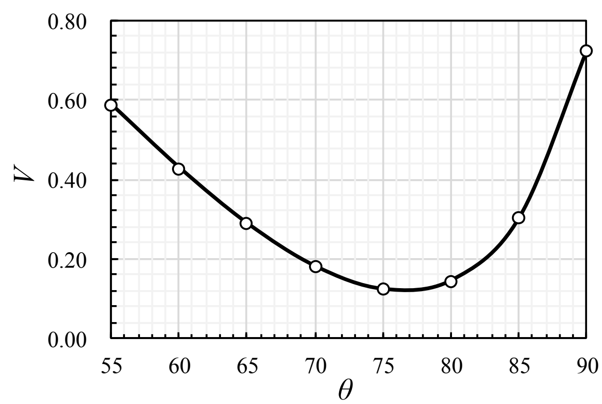

Figure 4. Relationship between the tilting angle of a human body (θ) and the value of V.

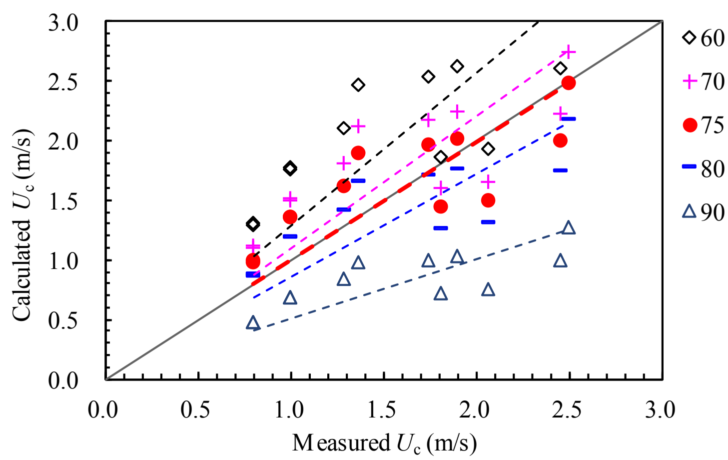

Figure 5. Comparison between the calculated and measured values of U_c (the dash lines represent the linear fitting curves when θ= 60°, 70°, 75°, 80°, 90° from top to down).

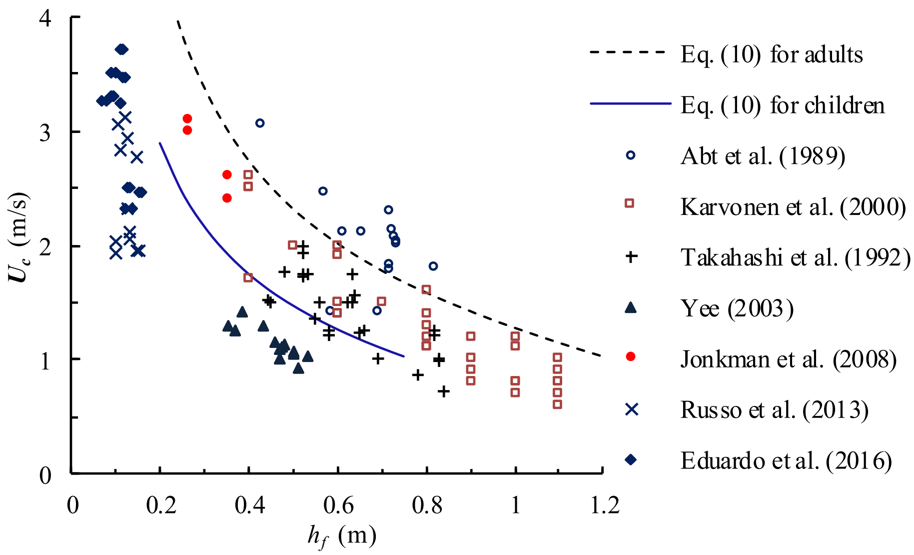

Figure 6. Comparison between the flume measurements and the calculations using the derived formula for adults and children.

Table 1. Calibrated parameters in Eq. (10) using the measurements in the literature

Experimental data	α	β	R^2	Number of observations
Abt et al. (1989)	3.672	0.271	0.712	14
Karvonen et al. (2000)	2.471	0.202	0.959	34

Table 2. Parameter calibration using 74 tests and verified results using 12 tests

θ	Calibration (74 tests)		Verification (12 tests)
	α	***β***	***V***
55	1.990	0.287	0.586
60	2.110	0.288	0.428
65	2.265	0.290	0.288
70	2.470	0.293	0.180
75	2.757	0.297	0.123
80	3.186	0.303	0.145
85	3.945	0.316	0.302
90	5.789	0.353	0.724

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